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Chapter 8

An Approach to Building Musical Bioprocessors with *Physarum polycephalum* Memristors

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Abstract This chapter presents an account of our investigation into developing musical processing devices using biological components. Such work combines two vibrant areas of Unconventional Computing research: *Physarum polycephalum* and the memristor. *Physarum polycephalum* is a plasmodial slime mould that has been discovered to display behaviours that are consistent with that of the memristor: a hybrid memory and processing component. Within the chapter, we introduce the research's background and our motives for undertaking the study. Then, we demonstrate *Physarum polycephalum*'s memristive abilities and present our approach to enabling its integration into analogue circuitry. Following on, we discuss different techniques for using *Physarum polycephalum* memristors to generate musical responses.

8.1 Introduction

Computer musicians, perhaps more than any other discipline-specific group in the arts, have always looked to technology to enhance their metier. Indeed, in Computer Music (CM), we have a rich history of experimenting with obscure and emerging technologies. Such technological curiosity extends back to the field's genesis where computer scientists in the 1950s manipulated the architectures of the early computing machines to play renditions of popular melodies. Since these playful experiments, the field of music has remained tightly interlaced with the computer. Subsequently, music is an inherent beneficiary of advances in computer hardware (Doornbusch 2009). For example, the development of the Digital Audio Converter (DAC) gave us advanced computer sound synthesis and the internet gave us mass non-tangible distribution of music. Therefore, it is likely that future developments in computing technology will have a profound impact on music.

The field of Unconventional Computing (UC) looks to develop new approaches to computing that are based on the data processing abilities of biological, chemical, and physical systems. Such approaches aim to go beyond or enrich our current

models of computation. Notable experiments have been developed to demonstrate the feasibility of building computers using reaction-diffusion chemical processors (Adamatzky et al. 2003) and biomolecular processors exploring the self-assembly properties of DNA (Shu et al. 2015). We are interested in how these new concept computers may provide future pathways for music. Historically, most UC research has been out of reach for the vast majority of computer musicians: they required expensive lab equipment, specialist handling, and a good grasp of complex underlying theory. Recent research, however, is suggesting that there may be an accessible alternative.

The plasmodial slime mould *Physarum polycephalum* (Figure 8.1), henceforth *P. polycephalum*, is a biological computing substrate that requires comparatively fewer resources than most other UC prototypes. This organism is easy to look after, safe to use, and inexpensive to acquire and maintain. Such attributes are unique in UC and enable non-biologists to obtain and experiment with the organism. As a result, engineers and computer scientists have been able to implement sensing and computing prototypes using living biological material. The plasmodium of *P. polycephalum* is a large single cell that is visible to the unaided human eye. Although without a brain or any serving centre of control, the plasmodium is able to respond with natural parallelism to the environment around it. The organism propagates on gradients of stimuli while building networks of protoplasmic tubes that connect foraging efforts and areas of colonisation. These tubes serve as a distribution network for intracellular components and nutrients.

The route-efficient nature of the plasmodium’s protoplasmic network, which it is able to dynamically reconfigure over time and responds to stimulants with parallelism, gained the interest of researchers in the field of UC as a way to calculate pathways. Here, several research groups developed mazes, 3D landscapes, and terrain models to experiment with the organism’s ability to create efficient pathways to sources of food while avoiding areas that contain repellents (Adamatzky 2012). The amount of UC research into *P. polycephalum* has increased exponentially within the last decade or so (Nakagaki et al. 2000). Researchers have developed an impressively diverse and vibrant range of experimental prototypes exploiting the organism’s information processing abilities. Some examples are colour sensing (Adamatzky 2013), robot manoeuvring (Tsuda et al. 2007), and logic gate schemes (Whiting et al. 2014, Adamatzky & Schubert 2014, Adamatzky et al. 2016). See (Adamatzky 2015) for a survey of *P. polycephalum* prototypes. Such a span of experimental proofs has led to one *P. polycephalum* advocate describing the organism as the “*Swiss knife of the unconventional computing: give the slime mould a problem it will solve it*” (Adamatzky 2015, p.1). As *P. polycephalum* has made UC prototyping feasible for computer scientists and engineers, it may also provide a potential gateway for computer musicians who want to explore UC creatively.

In our research, we have been investigating the feasibility of engineering unconventional and novel hybrid hardware-wetware computing systems for music and sound with the plasmodium of *P. polycephalum*. Our initial work built on the early UC experiments where the organism’s unfolding protoplasmic network created sequences of musical events for algorithmic composition; please refer to Chapter 2

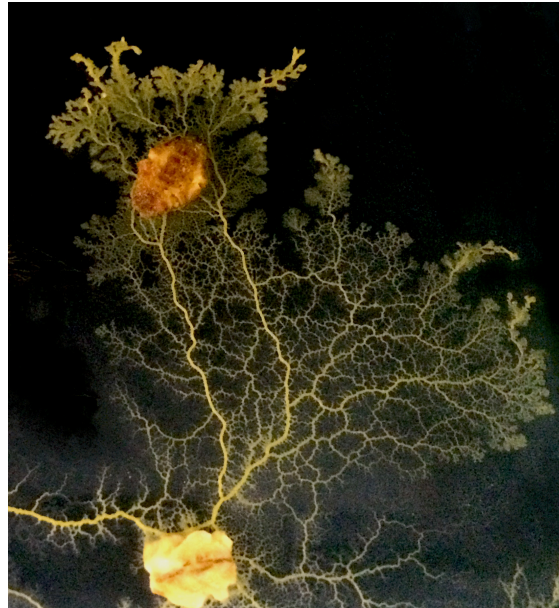


Fig. 8.1 The plasmodium of *P. polycephalum*

in this volume for more details. We enriched this approach by recording the organism's extracellular membrane potential, which we embedded into a step sequencer architecture to extend its conventional remit by regulating sound event triggering (Braund & Miranda 2015*b*). This electrical behaviour has a rich spectrum of oscillations, which can be used to accurately denote spatial progressions and the organism's physiological state (Adamatzky & Jones 2011). These research progresses, however, required behavioural data gathered from an experimental process beforehand. Thus, they did not use the organism in realtime. Such an experimental process creates a large obstacle that limits the extended usability of the systems: using the same set of behavioural data will result in similar outputs each time. This constraint could be avoided by gathering more data, but this process takes several days and would be tedious. To progress with our research, we needed to find ways of harnessing the organism's information processing abilities as close to realtime as possible.

8.1.1 *The Memristor*

In 2013, Gale, Adamatzky & Costello (2013) demonstrated in laboratory experiments that the protoplasmic tube of *P. polycephalum* can act as an organic memristor. *P. polycephalum*'s memristive investigations began in 2008 when Saigusa et al. (2008) ran experiments which demonstrated that plasmodia can anticipate periodic events. Shortly after, Pershin et al. (2009) published a paper that described the plas-

modium's adaptive learning behaviour in terms of a memristive model. Gale's work built on these research progresses and has provided the basis for other researchers to develop memristor and memristor-transistor prototypes (Tarabella et al. 2015, Romeo et al. 2015).

The memristor is the fourth fundamental passive circuit element that relates magnetic flux linkage and charge; the other 3 types of circuit elements are resistors, capacitors and inductors. It was theorised by Chua (1971) in 1971 but not physically demonstrated until 2008 (Strukov et al. 2008). The word memristor is a contraction of 'memory resistor', which describes the element's function: a resistor that remembers its history. Memristors alter their resistance as a function of the previous voltage that has flown through and the time that it has been applied. Furthermore, when you stop applying voltage, the memristor retains its most recent resistance state. For a detailed introduction to the memristor, please refer to Chapter 6 in this volume.

In contrast to the other three fundamental elements, memristors are intrinsically nonlinear. We can observe such nonlinearity in its I-V profile, which takes the form of a pinched hysteresis loop when applied with an AC voltage - a Lissajous figure formed by two perpendicular oscillations creating a high and low resistant state. Hysteresis is where the output of a system is dependent on both its current input and history of previous inputs. The memristor's most defining characteristic is its hysteresis. Chua's paper described an ideal memristor's hysteresis as a figure of 8 where the centre intersection is at both zero voltage and current (Figure 8.2). We can observe the element's memory function in this profile where each voltage has two current readings, one on the ramp up to maximum voltage and one on the ramp down. The magnitude of hysteresis lobe size changes as a function of both the frequency of the AC voltage and the memristive system's response time. We can describe memristance using a state-dependant Ohms law, which mathematically is denoted below:

$$M = R(q) = \frac{d\phi(q)}{dq} \quad (8.1)$$

where q is charge and ϕ is flux.

This component is exciting computer scientists due to properties that have potential to revolutionise the way our computers function by eradicating the distinction between memory and processor. Moreover, the component's behaviour has been found to be analogous to certain process in the brain, which is giving rise to perspectives of developing 'brain-like' computers (Versace & Chandler 2010).

Although interest in memristors is thriving, there are accessibility issues that limit the extent of which people can experiment. Currently, the component is not yet commercially available and is difficult for researchers to fabricate in the laboratory (Gale, Adamatzky & Costello 2013). HP labs are one of a number of groups that are attempting to develop a commercial memristor (Strukov et al. 2008). However, the discovery that *P. polycephalum* can act as a memristor is providing an alternative approach to begin developing everyday information processing systems using memristors grown out of biological material.

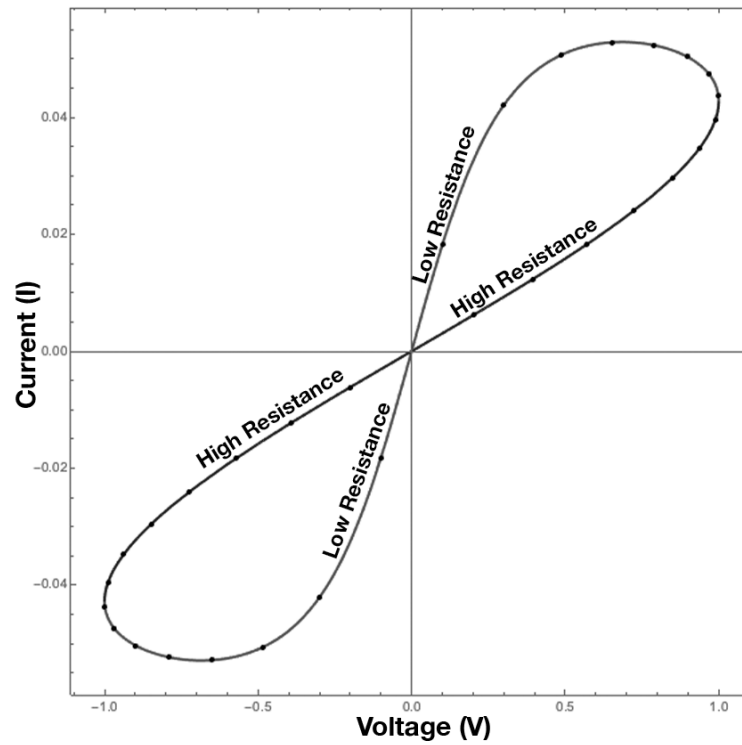


Fig. 8.2: Example of hysteresis in an ideal memristor (arbitrary values used).

In regards to music, the memristor's abilities could enrich our approach to developing creative computer music tools. In particular, we hypothesise that the component's ability to alter its internal state according to its history and current input may prove to be a productive approach to implementing systems to aid composition and for real-time improvisation. In this chapter, we explore the feasibility of engineering biological processing systems using *P. polycephalum*-based memristors for music. Here, we discuss and present approaches to generating responses to musical inputs.

The remaining of this chapter is structured as follows. First, we give a brief insight into how we culture the organism for our research and demonstrate *P. polycephalum*'s memristive properties. In the next section, we lay out the development of receptacles that allow for the organism to be encompassed into an electrical device. Following on, the chapter presents two different approaches to generating musical responses to seed material. Finally, we conclude with future work and final remarks.

8.2 Harnessing *P. polycephalum* as a Memristive Component

When conducting our research with the plasmodium, we maintain a farm that adapts techniques from (Adamatzky 2010), using a specimen from Carolina Biological¹. Here, we culture plasmodium in plastic containers with several small air holes in the lid (Figure 8.3). The organism lives on a 2% non-nutrient agar substrate ($\approx 7\text{mm}$ thick) and is fed with oat flakes twice daily. Cultures are kept at room temperature and once a day we remove the remains of any digested oat flakes. Every week the plastic container is cleaned and the organism is replanted onto fresh agar.

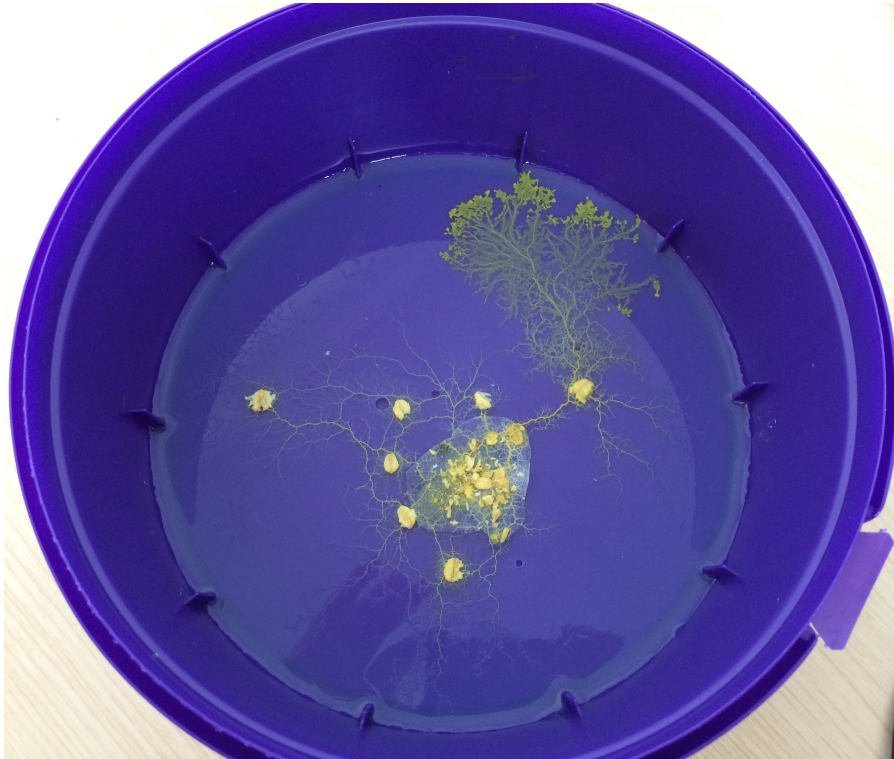


Fig. 8.3: A plasmodium farm cultured within round plastic containers on a 2% non-nutrient agar.

Initially, implementing *P. polycephalum* memristors was difficult and impractical. Components were grown in small Petri dishes that we retrofitted with electrodes comprised of a circle of tinned copper wire filled with non-nutrient agar. To manipulate the plasmodium to lay down the required protoplasmic tube, we would position

¹ www.carolina.com Last Accessed: 28th August 2016

a colonised oat from our farm on one of the electrodes and a fresh oat flake on the other. This arrangement influences the plasmodium to propagate along a chemical gradient to the fresh oat, resulting in a protoplasmic tube linking the two electrodes. As the organism does not like growing over dry surfaces, we would fix damp paper towels to the inside of the Petri dish lids to keep humidity high. Figure 8.4 depicts a *P. polycephalum* memristor that we implemented using this set up.

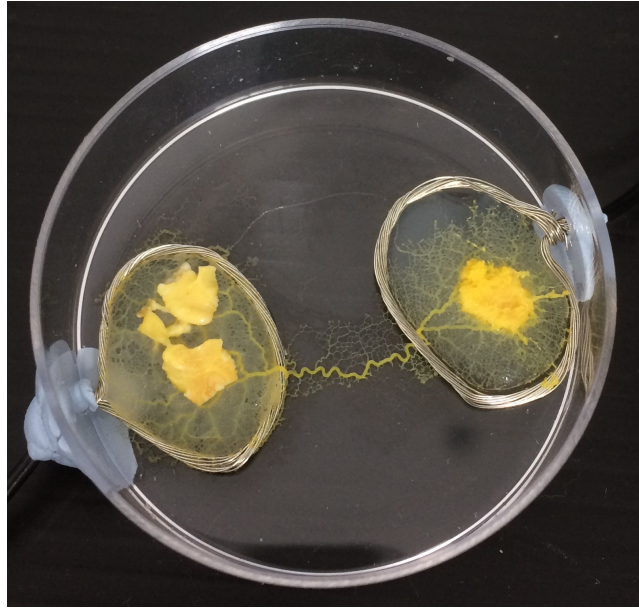


Fig. 8.4: A photograph of a *P. polycephalum*-based memristor implemented in a 60mm Petri dish. Shown is two electrodes comprised of a circle of wire filled with non-nutrient agar, linked by a protoplasmic tube.

In (Braund et al. 2016), we ran comprehensive experiments to confirm Gale et al.'s (2013) findings and to begin understanding the nature of these biological components. For these experiments, we set up 20 samples to run tests on. It took circa 30 hours for the plasmodium to produce the required protoplasmic tube, with an overall success rate of 100%. We tested these protoplasmic tubes under a range of different voltages and frequencies. Voltage sine waves were fabricated from 160 discrete values in the ranges of $\pm 50\text{mV}$, 100mV , 200mV , 250mV , 500mV , 600mV , 1V , and 1.5V , with frequencies of $\Delta t = 0.5, 1, 2$ and 2.5 seconds.

Results from our experiments suggest that a $\Delta t = 2\text{s}$ and voltage range in excess of $\pm 500\text{mV}$ worked best for producing pinched I-V curves. Figure 8.5 shows four I-V profiles from our experimentation. Upon comparing these profiles with that of an ideal memristor's (Figure 8.2), it is apparent that *P. polycephalum* memristors are not ideal. Measurements on the organism produced highly asymmetrical I-V

curves with pinch points that are offset from origin. Furthermore, each organism's curve is different and, in several cases, curves have multiple pinch points. One of the characteristics that classify a memristor as 'ideal' is that it does not store energy; a memristor is a passive circuit component. Therefore, the hysteresis pinch points should singular and at 0 voltage and current. In (Chua 2015), Chua explains that if such an offset of hysteresis pinch points from the origin can be modelled by the addition of circuit elements, then the device is classified as an imperfect memristor. In this case, the plasmodium's intracellular activity acts as a kind of power source that oscillates. Therefore, we can class the protoplasmic tube as an imperfect memristor.

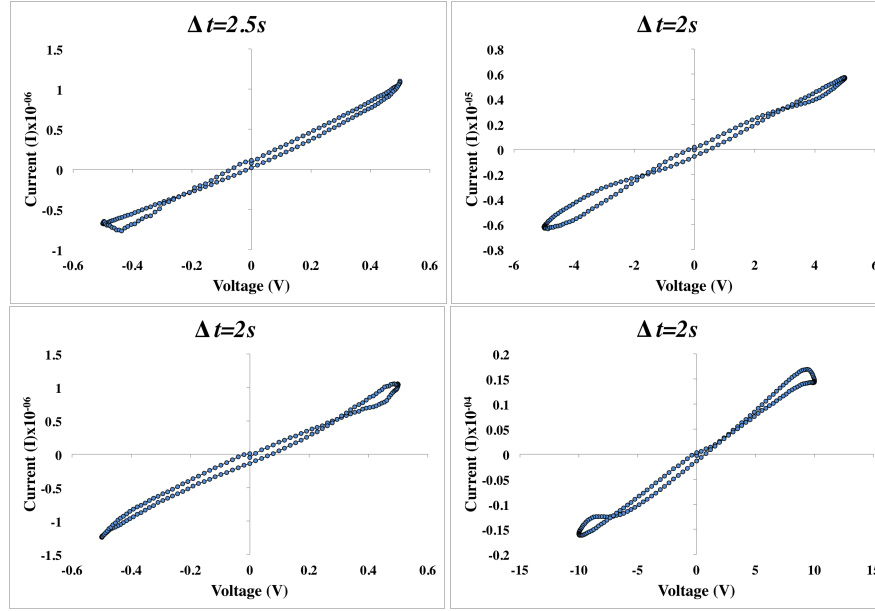


Fig. 8.5: Four pinched I-V curves measured on the protoplasmic tube of *P. polycephalum*. Results with these samples presented a high degree of variation sample-to-sample. Furthermore, in several cases, the memristive curves had several pinch points, as depicted in the two graphs on the right-hand side.

In regards to our musical intentions, it is intriguing that memristive properties differ organism-to-organism because it suggests that we may be able to control its degree of non-linearity. Thus, it is plausible to envisage CM systems that can produce different sounding responses by implementing different classes of *P. polycephalum* memristors. By different classes we mean different instances of hysteresis, which is discussed in (Chua 2015).

Memristance is an effect that varies system-to-system according to nature of the memristive mechanism. In some memristors, for example, the mechanism is the movement of oxygen vacancies amongst two thin films of titanium dioxide sand-

wiched between two electrodes (Strukov et al. 2008). The application of AC voltage moves the oxygen vacancies creating a high resistance when the current goes in one direction and a low resistance when it goes in the other direction. Due to the complexity of biological systems, it can be hard to say what mechanism causes memristive observations. In the case of *P. polycephalum*, there are a number of biological processes that could cause the I-V profiles displayed in Figure 8.5. Firstly, the plasmodium shuttle streams a fluid cytosol endoplasm containing ions such as Ca^{2+} and H^+ (calcium and hydrogen, respectively) around its protoplasmic tubes (Guy et al. 2011, Coggin & Pazun 1996). A sudden change in streaming direction could cause a resistance state switch and explain why pinch points are offset. However, streaming switches polarity at intervals ranging from a few seconds to a few minutes with an average interval of approximately 1.3 minutes (Wohlfarth-Bottermann 1979), which is longer than the period of any of the test waveforms. We believe it is more likely that the application of voltage is causing the cell to alter intracellular concentrations of certain ions, which, in turn, will alter the cell's electrical resistance. It may be the case that our test voltage waveform is activating one or more voltage-gated ion channel, causing the organism to take in or expel ions. Such a hypothesis would explain why cells with varying morphologies, and thus different quantities of biological components with different spatial configurations, produce different I-V profiles. Further research is needed to gain a better understanding of this.

8.2.1 Receptacles for Culturing Slime Mould Memristors and Component Standardisation

The results presented in the previous section showed that the protoplasmic tube of *P. polycephalum*, under the appropriate timestep and voltage range, exhibits I-V curves that are consistent with that of a memristor. However, if we were to develop systems for CM using these biological components, we first needed to address some practical issues. Our method of implementing the memristors was empirical and unrealistic to encompass into a device for the average computer musician. Fitting petri dishes with the necessary electrical parts was tedious and fiddly. Moreover, the setup provides no protection to delicate components. As a result, often components become electrically disconnected when moving them from the culture cabinet to where they are required. Another limitation of the setup is the component's lifespan. It takes circa 30 hours to grow a component that remains functional for \approx two days. Growth time is likely due to conditions not being well delineated: within the Petri dishes the organism has a number of different propagation trajectories and grows in a random fashion. As a result, components have a high degree of morphological variation component-to-component. Memristive observations also differ vastly between organisms, which, although suggests potential benefits, needs to be better controlled.

In order to render *P. polycephalum* memristors into a stable component, we developed receptacles that can be easily integrated into a circuit, standardised growth conditions, delineated propagation trajectories, encapsulated the organism into a stable microenvironment, and standardised electrical properties. As one of the key criteria for our research with *P. polycephalum* is accessibility for computer musicians, we choose to explore using 3D printing techniques to fabricate our receptacles. In major part, commercially available 3D printers use the additive stereolithography fabrication method. These machines use rolls of inexpensive filament that are available in a variety of materials. For the work presented in this chapter, we used a Lulzbot Taz 5² stereolithography printer and Autodesk's free 123Design software³.

To use the plasmodium's protoplasmic tube as an organic electronic component, we needed the organism to forge its tube between two electronically isolated electrodes. Thus, the tube cannot reside on an agar substrate. The organism does, however, require a high level of humidity. To achieve these requirements we designed two chambers that connected via a tube. Here, the tube is interchangeable to allow us to investigate the effect of protoplasmic tube length on memristance. The chambers have a well to accommodate 1.5ml of agar to achieve a favourable level of humidity. To delineate the growth of the protoplasmic tube, we fabricated the chambers with High Impact Polystyrene (HIPS) as the organism does not like this substance (Gotoh & Kuroda 1982). Consequently, the plasmodium will be discouraged from growing on the walls of the chamber and encouraged to propagate across the linking tube to the other chamber, laying down the desired protoplasmic tube.

As the plasmodium does not like propagating over bare metals, we chose to avoid using metal electrodes in favour of more biocompatible materials. We opted to use a newly developed conductive polylactic acid (PLA) 3D printing material⁴. PLA is Food and Drug Administration certified and, due to its high biocompatibility, is widely used in the medical field (Gupta et al. 2007). The conductive PLA has a volume resistivity of $0.75\Omega\text{-cm}$. Using this material, we printed two collars that slotted into the chambers. Each collar was designed with an electrical contact point and a rim to attach the linking tube between the chambers. For the linking tube we used off the shelf medical grade polyvinyl chloride (PVC) tubing, which is available in a variety of inner and outer tube dimensions. As the aim is to limit the organism's growth space, we used tubing that had a 4mm inner diameter and 6mm outer diameter.

In (Braund & Miranda In Press), we ran extensive tests on our receptacles while using the aforementioned setup as a control. With the delineated growth environment, growth time decreased to under 10 hours, and, throughout our testing, every sample grown in our receptacles forged the required protoplasmic tube. Memristive effects were also more prevalent at lower voltage ranges. Here we had good success at 250mV. In regards to hysteresis morphology, we found there to be a strong relationship both in single sample curves measured at different time steps and volt-

² <https://www.lulzbot.com/> Last Accessed: 28th August 2016

³ <http://www.autodesk.co.uk/> Last Accessed: 28th August 2016

⁴ <http://functionalize.com/> Last Accessed: 28th August 2016

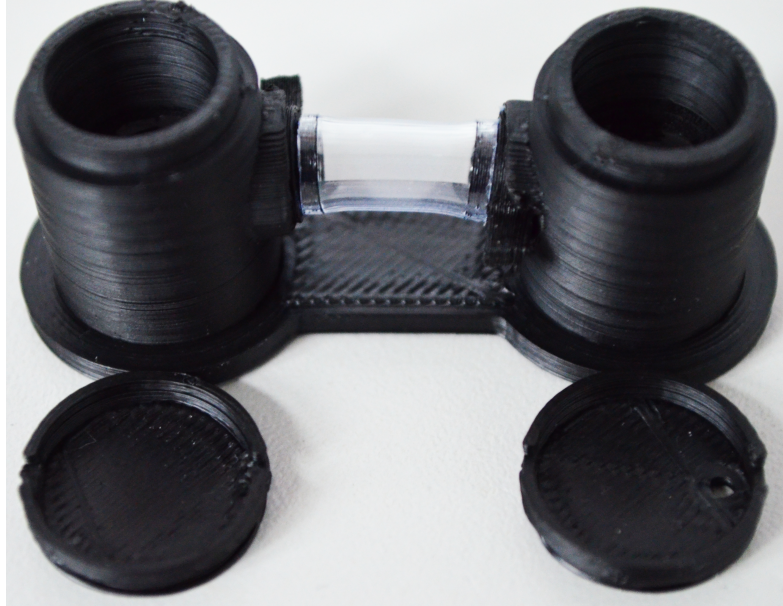


Fig. 8.6: A photograph of our receptacle. Shown is two identical growth chambers, two lids (one with and one without an air hole), two conductive electrode collars and a 10mm base.

age ranges, and sample-to-sample curves. That is, hysteresis loops had relatively consistent lobe sizes as well as pinch locations, which is depicted in the graphs in Figure 8.7. We also investigated component lifespan by performing measurements on each sample once a day until they presented no memristive curves. Here, all samples maintained their memristance for at least 7 days, with 3 samples reaching twice that.

8.3 Approaches to Processing Music with *P. polycephalum*-based Memristors

Our receptacles have established more consistent, robust, and rigorous methods of implementing *P. polycephalum*-based memristors that facilitates the component's integration into circuitry. These developments allowed us to begin experimenting with approaches to harnessing the components for music. In this section, we present two systems that generate musical responses using different approaches. The first was our initial work that was aimed at building an understanding of the memristor's input to output space where we experimented with simple note to voltage and current

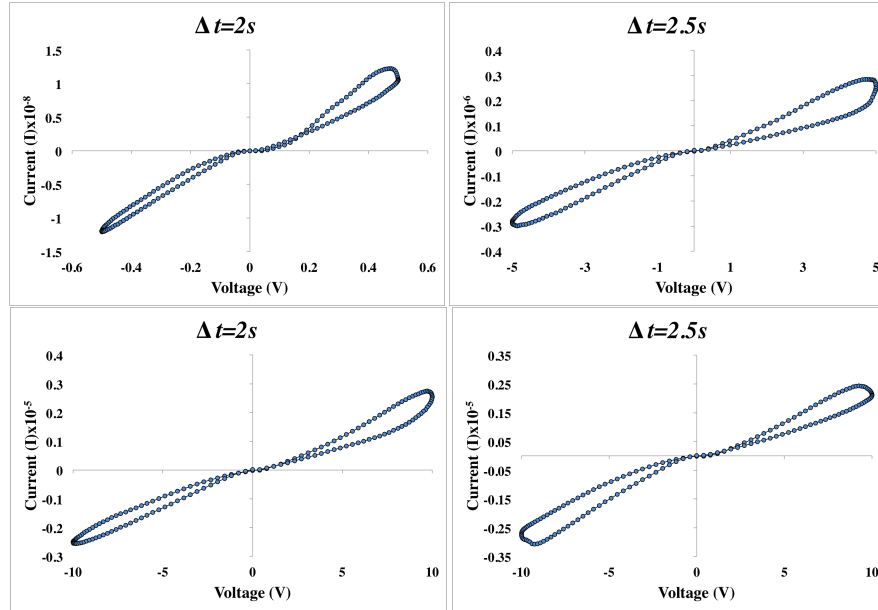


Fig. 8.7: Four examples of pinched I-V curves measured with samples grown in our receptacles. Notice how each curve is morphologically similar in regards to location of pinch points and lobe size.

to note mappings. The second was a more complex multimodal system that took inspiration from the component's brain-like behaviour.

To implement the systems, we used a combination of the following hardware. Two Keithley 230 programmable voltage sources provided methods of data input to the memristors in the form of analogue voltages while two Keithley 617 programmable electrometers allowed for measuring the component's response. These devices were interfaced with custom software using ProLogix GPIB-USB controllers. All software were programmed in Cycling 74's Max environment. USB relay boards facilitated switching between different memristors.

8.3.1 A Basic Mapping System for Generating Pitches

To start our musical experiments, we choose to explore generating responses to one musical parameter, pitch; at this point, we did not consider note durations, loudness, or rhythmic structure. By limiting our first attempt to one parameter, we were able to gain a clear appreciation of how to best approach harnessing a memristor's input-output space for music. Moreover, we wanted to experiment with the basics of simple note transformation before building a complex multimodal system. Thus,

as we are only working with pitches, all this section's examples are displayed with notes that have the same arbitrary duration, loudness, and rhythm.

P. polycephalum memristors are analogue components whose input parameters include voltage and frequency, and output parameters include current and measurement offset. In the first instance, we were interested in finding the most transparent and straightforward approach to encoding musical information for inputting into a memristor and transcribing its subsequent output to generate a reply. As such, we took one of each of the memristor's input and output parameters and adopted a direct transcription approach. Here, we decided to encode pitch information at note level using discrete voltages and generate a response by transcribing subsequent current readings into notes. A flow diagram of this approach is displayed in Figure 8.8.



Fig. 8.8: A flow diagram of our basic mapping approach for generating pitches using a memristor.

To implement this approach, we developed software that works as a translator between incoming music and *P. polycephalum* component. The software first requires the user to input a vocabulary of pitches for the system to use. Here, the user has two options: they can either input a custom vocabulary or inform the software to generate responses only with notes contained within the input. This process allows the software to assign a unique voltage value to each note in the vocabulary within the range of 0-1V, with 0V and 1V reserved for component calibration purposes. At this early stage of the investigation, we have adopted a logical note-to-voltage transcription process where the system assigns note voltages in ascending order according to pitch. Table 8.1 demonstrates this process for a vocabulary containing every note in an extract to the introduction of Nimrod, by Edward Elgar, which is depicted in Figure 8.9.

The system is programmed to accept input as MIDI data, either in the form of a live MIDI instrument or single track MIDI file. As music is played in, our software transcribes each note into its respective voltage value. Then, in batches of 15 notes, or 10-second's worth of notes, these voltages are put together to form a discretized waveform with a static timestep of 2-seconds. During this process, note voltages are considered absolute values: for example, -0.5V and 0.5V are the same note. To input the notes as an AC waveform, 2 batches create one wave cycle, with batch 2 using the negative voltage domain. In order to calibrate the current-to-pitch transcription process, the calibration voltages are placed between each batch to create the wave's crest and trough. Figure 8.10 depicts the input waveform for Nimrod (Figure 8.9), using the voltage vocabulary detailed in Table 8.1.

Once the system has enough notes to produce one wave cycle, it instructs a Keithley 230 voltage source to begin applying the waveform to a *P. polycephalum* memristor. At each voltage step, and interfacing with a Keithley 617 programmable elec-

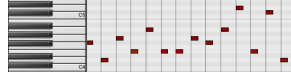


Fig. 8.9: An extract of the introduction melody to Nimrod, by Edward Elgar.

Table 8.1: The note-to-voltage transcription process for every note in the melody depicted in Figure 8.9.

Music Note	MIDI #	Voltage
C4	62	125 mV
E4	64	250 mV
F#4	66	375 mV
G4	67	500 mV
A4	69	625 mV
C#5	73	750 mV
D5	74	875 mV

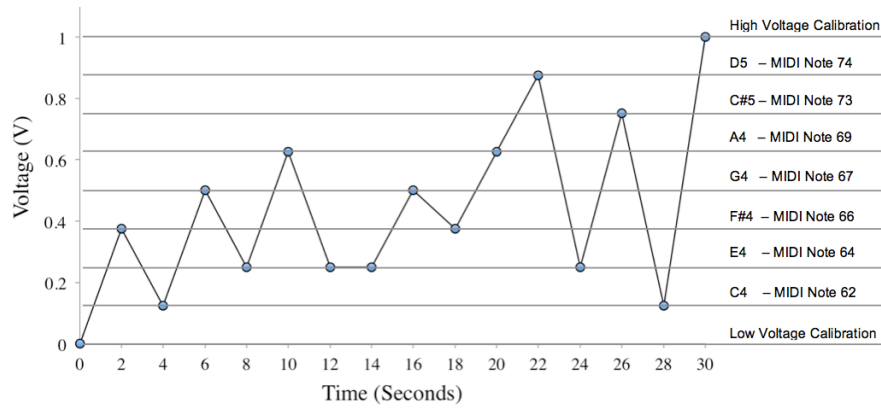


Fig. 8.10: The input voltage waveform for the introduction melody to Nimrod (Figure 8.9).

trometer, our software takes an instantaneous current measurement. Readings taken at the calibration voltages are then used to map the other measurements into MIDI notes. This procedure is derived from the note-to-voltage transcription stage: higher current measurements result in higher pitched notes. The graph pictured in Figure 8.11 is an overview of the input-to-output mapping procedure for Nimrod. Here, the dotted line is the input voltage sequence while the black line is the memristor's response. The shaded boxes portray seven discrete magnitudes of current that the readings are quantised into. Each of these corresponds to one of the seven notes in the system's vocabulary.

An analysis of our system's response to Nimrod (Figure 8.12) is presented in Table 8.2 where we looked at the directional movement between successive notes within the system's vocabulary. The analysis shows a reduced movement between notes in the response sequence when compared against the input. The absolute average of the movement between notes is 1.3 for the response, which is half of the

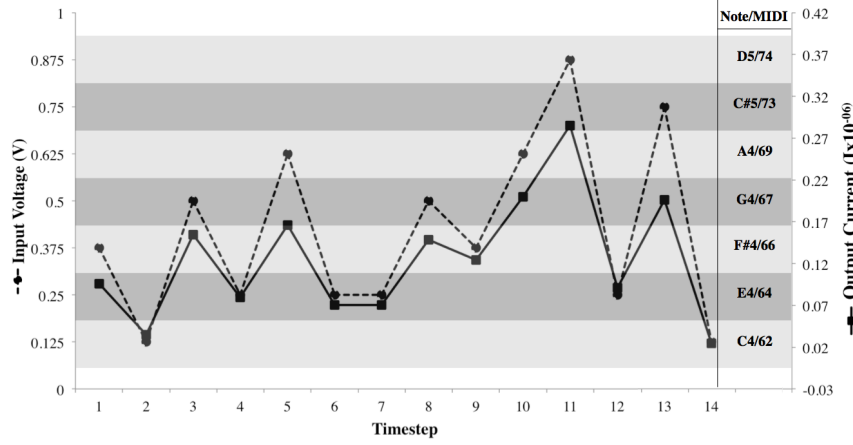
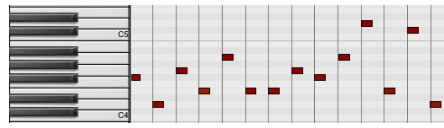
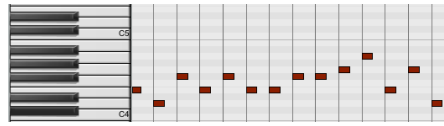


Fig. 8.11: An overview of the input-to-output mapping procedure exemplified using the extract to Nimrod in Figure 8.9.

input's average at 2.6. This reduced movement is likely down to two reasons. Firstly, the memristor takes longer to respond to higher changes in voltage. Secondly, a *P. polycephalum* memristor is in a low resistant state when the voltage is increasing, and a high resistant state when the voltage is decreasing. In the case of Nimrod, for example, where MIDI note 64 follows 74, the voltage change is -625mV, which causes a higher resistance and larger voltage change than when note 67 follows 64 (+375mV). Referring to Table 8.2, the distance between sequential notes in the input and output melody movement columns supports this hypothesis. Here, the input's highest movement is -5, whereas the output's largest movement is -3.



(a) Nimrod Input.



(b) Nimrod Output.

Fig. 8.12: An example where our system generated a response to Nimrod, by Edward Elgar.

Input			Output			Input-Output Transformation
MIDI Note	Note #	Melody Movement	MIDI Note	Note #	Melody Movement	
66	3	-	64	2	-	-1
62	1	-2	62	1	-1	0
67	4	3	66	3	2	-1
64	2	-2	64	2	-1	0
69	5	3	66	3	1	-2
64	2	-3	64	2	-1	0
64	2	0	64	2	0	0
67	4	2	66	3	1	-1
66	3	-1	66	3	0	0
69	5	2	67	4	1	-1
74	7	2	69	5	1	-2
64	2	-5	64	2	-3	0
73	6	4	67	4	2	-2
62	1	-5	62	1	-3	0

Table 8.2: Analysis of the sequence of notes in our system’s response to Nimrod (Figure 8.12b).

We have extensively experimented with our system to explore its expressivity and input to output mapping space. Such experimentation spawned the artefact *Bio-Computer Music*, which is an experimental one-piano duet between pianist and plasmodial slime mould *P. polycephalum*, composed for live performance. A written summary of this piece can be found in (Braund & Miranda 2015a) while audio recordings can be sourced at (Miranda Last Accessed: 12 February 2015). Our results have highlighted that inputting musical notes as discrete voltages did not exploit the memristor’s input-output space in an appropriate way for music. Assigning voltages to notes in ascending order according to pitch causes higher interval transitions to occur less in the output. This is because the components need more time to react to larger changes in voltage and have a higher resistance when the voltage is decreasing.

8.3.2 An Interactive Musical Imitation System

In this section, we present our most recent attempt at harnessing *P. polycephalum* memristors for music generation. This endeavour takes the form of an interactive musical imitation system that generates complete responses by encompassing four *P. polycephalum* memristors.

For this system, we wanted to find more appropriate methods of harnessing the biological memristors to process music. In particular, we needed to build on our experience from the first musical experiments to devise suitable encoding methods to represent musical information on *P. polycephalum* memristors and develop task

models - the process by which the system processes and generates music - that flesh out their non-linear analogue nature. One area of memristor research that we were keen to take inspiration from for music generation is the comparisons between the component's behaviour and certain processes in the brain. Such comparisons have led to perspectives that the memristor may be able to revolutionise artificial intelligence (AI) (Schuster & Yamaguchi 2011, Versace & Chandler 2010): a field that has provided a lot of tools for computer-aided composition systems (Miranda 2013).

Numerous publications (e.g. (Snider 2008, Linares-Barranco & Serrano-Gotarredona 2009)) draw comparisons between the memristor and the way synapses function: the structure that allows neurones to transmit and receive signals from one another. In particular, the component's behaviour has been found to be relatable to Spiking-Time-Dependent Plasticity (STDP) in neural networks (Howard et al. 2012), which is the procedure where synapses alter their connection weight between neurones. STDP functions by one neurone sending an electrical spike to another neurone. The receiver neurone's synapse evaluates the importance of the incoming signal by contrasting it with its own state that it stores locally and the strength of the connection between the two neurones. The synapse then updates its state accordingly and sends the result of the comparison to the body of neurone two which may fire an impulse to another neurone (Figure 8.13). This process propagates across a neuronal network, which gives rise to complex spiking observations (Gale et al. 2014) and facilitates Hebbian learning.

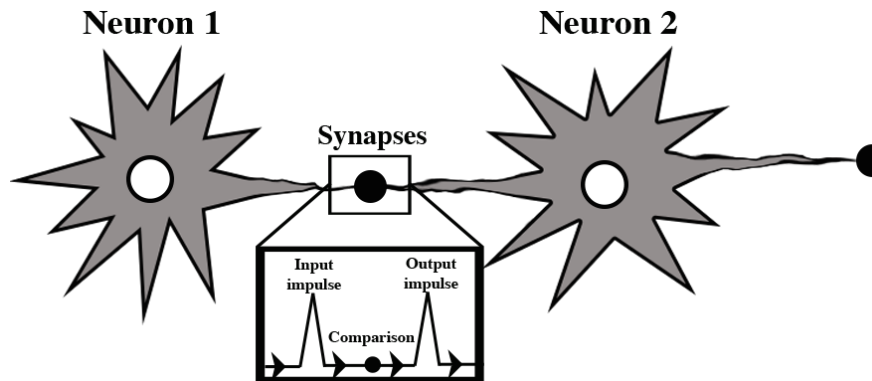


Fig. 8.13: The flow of information between two neurones.

STDP-like behaviour in memristors is an interesting concept to apply to the task of music generation because the process involves transitioning non-linearly between resistance states according to a memory that goes beyond the previous state (Gale, Matthews, Costello & Adamatzky 2013). Thus, the memristor's state alters according to both its history of inputs and the current input, which is relatable to the process of composing and improvising musical melody movements. However, implement-

ing networks of *P. polycephalum* memristors was beyond our research's stage of development. As such, we choose to draw inspiration from the communication process between two neurones, where the sending neurone represents system input, the receiving neurone is the system's output, and a *P. polycephalum* memristor represents the synapse between them. Here, we envisaged a musical system where memristor's output would trigger musical responses by transitioning between resistance states as a function of incoming electrical impulses that are representative of musical events. By comparison, the electrical impulse sent by neurone one would be an encoded musical event, where the magnitude of the impulse corresponds to the event's popularity in the input. Thus, the receiving neurone's synapse would be evaluating the importance of the impulse against its memory and altering its state based on how often the musical event occurred in the input. The output of the memristor, once decoded, would form part of the system's response. Figure 8.14 puts this concept into the practical terms of *P. polycephalum* memristors and the electrical measurement equipment.

By encoding musical data as a function of their occurrence, the memristor's response time can be a useful feature instead of a limitation: we can harness this attribute to help regulate the occurrence of less popular musical events in the output. Furthermore, we can augment this function by taking advantage of the way the component responds to reductions and increases in current. The transition between popular and less popular notes can dictate whether the input current increases or decreases, and, as such, whether the less popular note occurs in the output.

8.3.2.1 System Design

To implement this system, we developed software that, like the previous system, works with MIDI information for musical input. By using MIDI, we can generate responses to both live musicians and precomposed material in the form of MIDI files. To exemplify the music generation process in this description of our system's design, we use Bach's Gavotte en Rondeau as an example piece of melody (Figure 8.15).

To initiate the system, the user needs to set up a listening window, which can either be set to a user-defined duration or to the length of an input MIDI file. The listening window's function is to give the system time to generate sufficient response data before it begins to output. While listening, the system generates responses and saves them into a buffer until the window finishes. Once all the input material has been processed, the system either stops or starts processing its own output, depending on the choice of the user.

During listening mode, incoming MIDI information is split into four data streams of pitches, durations, loudnesses, and time between note-ons. The two time-domain attributes, durations and time between note-ons, are rounded to the nearest 100th millisecond, which quantises the incoming values. To enable the software to assign voltages to musical events according to popularity, it records the distribution

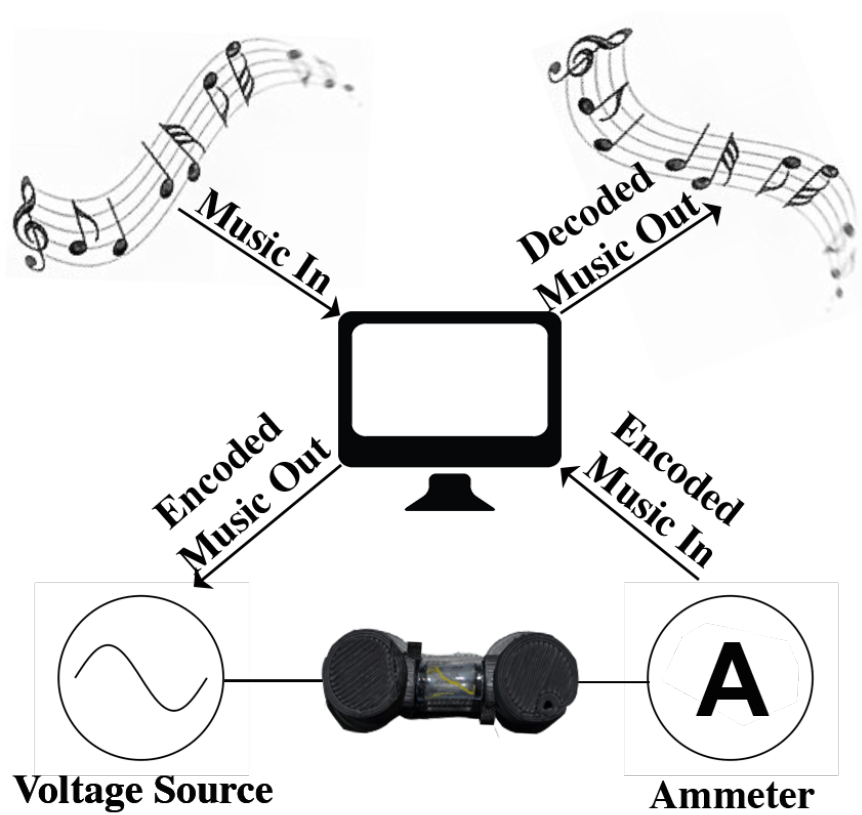


Fig. 8.14: An overview of the flow of information for our interactive music system.

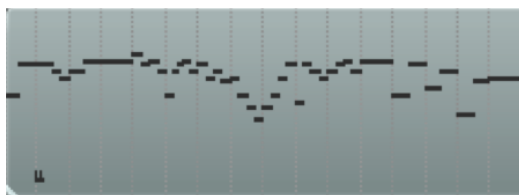


Fig. 8.15: The input notes from Bach's Gavotte en Rondeau.

for each of the incoming data streams. The MIDI pitch distribution for Gavotte en Rondeau is displayed in Figure 8.16.

	MIDI, qty;
1	MIDI, qty;
2	71, 10;
3	80, 18;
4	78, 20;
5	76, 12;
6	81, 12;
7	83, 2;
8	75, 4;
9	68, 4;
10	64, 2;
11	69, 2;
12	73, 2;
13	66, 2;
14	

Insertion Point Line: 1

Fig. 8.16: The MIDI pitch distribution for Bach’s Gavotte en Rondeau (Figure 8.15). The left column is populated with MIDI notes while the right column lists their respective occurrence.

In conjunction with the distributions, the system also maintains a count of the total amount of musical events. These values are used to distribute a voltage range of 10V amongst each of the recorded musical events where higher occurrences are assigned lower voltages. This is calculated as follows:

$$ImpulseVoltage = VoltageRange - \left(\left(\frac{TotalCount}{VoltageRange} \right) \times EventOccurrence \right) \quad (8.2)$$

For example, if the MIDI notes 60, 70, and 75 had occurred 1, 4, and 5 times, the software would assign them 9V, 6V, and 5V, respectively. The subsequent voltages make up the system’s vocabulary of impulses, which are continually updated as new MIDI data comes in.

Upon new musical events being input, the system updates the voltage distribution and calls the current event’s updated impulse voltage. This value is passed to a function that manages the input into the memristors, which is designed to take advantage of the organism’s nonlinear resistance profile. *P. polycephalum* components exist in a low resistance state when the voltage is increasing in magnitude and a high resistance state when the voltage is decreasing. Here, if the new event has occurred less than the preceding, the function increases the previous impulse by the event’s voltage. Conversely, if the event is less popular, the previous impulse value is decreased by the voltage. Thus, when moving from a lower occurring transition to a higher, the change in current will be greater. Once the system has calculated the voltage change for each of the four parameters (pitch, duration, loudness, and time between note-on), it coordinates the input and output process to the memris-

tors. The voltage impulse sequence for Bach's Gavotte en Rondeau is displayed in Figure 8.17.

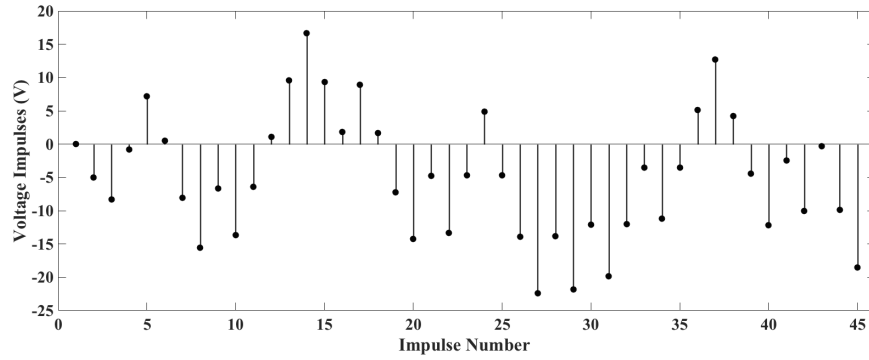


Fig. 8.17: The voltage impulse sequence for Bach's Gavotte en Rondeau (Figure 8.15)

The system encompasses four *P. polycephalum* memristors (Figure 8.18) that are assigned to pitch, duration, loudness, and time between note-ons. As we are currently limited to two sets of electrical input and output devices, memristors are wired into a USB relay board that facilitates switching between the four components. To make the system's design robust and portable, we designed a 3D printed box that houses the four memristor receptacles and the relay board (Figure 8.18).

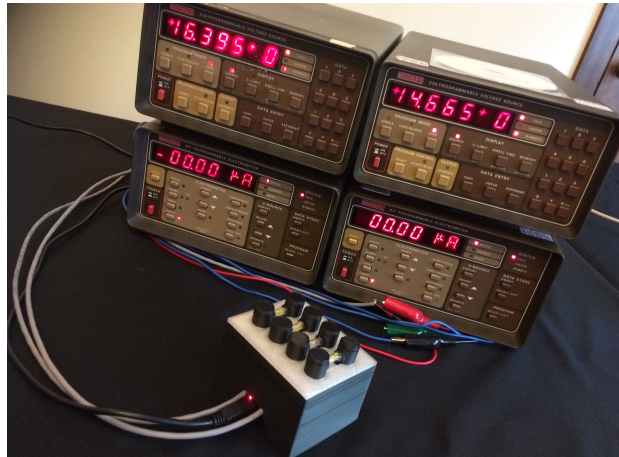


Fig. 8.18: A photograph of the hardware setup.

The system works with the memristors in pairs. First, the voltage impulses for pitch and loudness are sent simultaneously to their respective component. Then, interfacing with the electrometers, the software takes an instantaneous current reading from each of the two memristor's drain terminals. After which, it switches to the remaining two memristors and repeats the same procedure.

There are two user-defined parameters that control the current reading process: a step dwell time value (milliseconds) and a measurement offset percentage. The step dwell time informs the system of how long the impulse voltage is applied to the memristor before switching, and a measurement offset percentage dictates when to take the current readings. These two parameters allow the user to have control over the system's output. Figure 8.19 shows a *P. polycephalum* memristor's response to a change in voltage. This graph shows a sharp spike followed by a decay and eventually a sustained level of current. By examining this figure, you can see that the shorter the dwell time and measurement offset, the less time the memristor has to respond to the voltage change. Therefore, these two parameters dictate where on Figure 8.19's graph the system takes the current reading.

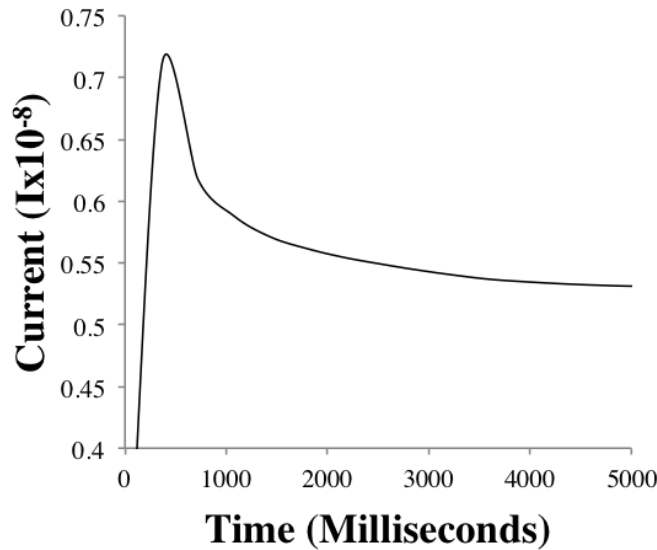


Fig. 8.19: An example of a *P. polycephalum* memristor's response to a sudden change in voltage.

To decode the current measurements into responses, the software maintains a transition matrix of inverted percentages for each of the four MIDI data streams. Here, each of the current readings is compared against its predecessor to calculate a percentage difference value. The software then looks up the transition percent-

ages belonging to the input musical event associated with the electrical impulses and selects the transition whose number is closest to the current reading's percentage difference value. By taking this approach, the system can only generate note transitions that have occurred at least once before. The four parameters (pitches, durations, loudnesses, and time between note-ons) are combined to produce an output musical event.

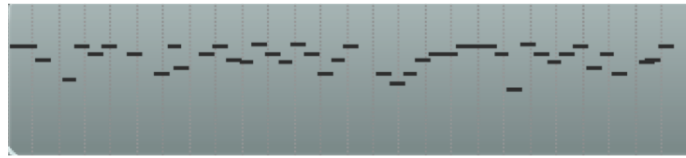
Figure 8.20 shows the input material and subsequent responses for Bach's *Gavotte en Rondeau*. In this case, we experimented with different dwell times and measurement offsets. The system was set up to generate responses using dwell times of 2-seconds and 4-seconds, and offsets of 50% and 75%. By studying the note distributions in Figure 8.20, it is clear that the longer dwell time and offset responses produced music that is more reminiscent of the input. This is because the system is allowing the memristor more time to respond to a change in voltage across its terminals. Thus, the shorter dwell times and measurement offsets are likely to cause larger differences between successive current readings (as shown by the graph in Figure 8.19). In turn, elevated difference values will cause the system to output less popular transitions, which, dependant on the distribution of the input material, could result in somewhat repetitive responses. Such a phenomenon could also explain why the first two responses in Figure 8.20 are significantly longer than the input. In all three cases, the system responded with fairly static note durations, which is likely due to the input durations being rounded to the nearest 100th millisecond.



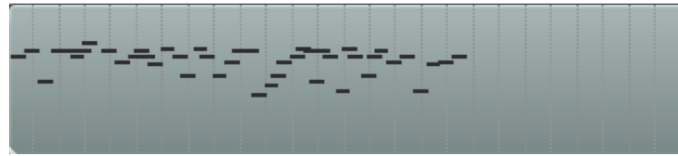
(a) Input notes from Bach's Gavotte en Rondeau.



(b) Dwell time 2-seconds, measurement offset 50%.



(c) Dwell time 2-seconds, measurement offset 75%.



(d) Dwell time 4-seconds, measurement offset 75%.

Fig. 8.20: Three examples of the system's responses to Bach's Gavotte en Rondeau.

8.4 Concluding Discussions

In this chapter, we have presented an overview of our work towards engineering musical systems with *P. polycephalum* memristors. As far as we know, the systems presented in this chapter are the first to harness biological circuit components to generate music. Although our work with *P. polycephalum* has progressed considerably, there are several areas that we need to further investigate.

As it currently stands, our systems rely on several large pieces of electrical equipment and a conventional computer. Such a setup is difficult to transport, expensive, and time-consuming to wire together. Thus, the next step is to develop a purpose-made device that is compact and cost-efficient. The plan is to replace the electrical measurement equipment and conventional computer with microcontroller boards. As part of this process, we will address some of our system's limitations. For example, to increase processing speed, the new device will be able to address more than

two memristors simultaneously. It should also be possible to integrate a larger total quantity of memristors, allowing us to develop more sophisticated approaches to musical generation. For example, the system could respond to a pianist by processing their left hand and right hand independently, or it could generate responses for several different instruments at once. Moreover, we could experiment with networks of interacting memristors to take advantage of their 'brain-like' behaviour.

In regards to the components themselves, we have begun addressing inherent issues of using biological entities as electrical components, standardisation, robustness, and lifespan. Biological systems are complex and respond to their local environment. The plasmodium of *P. polycephalum* is amorphous; thus, the quantity and configuration of biological components vary cell-to-cell. We observed the effects of such variation in the electrical measurements presented in Section 2, where I-V hysteresis differed between organisms. The development of our receptacles (Section 8.2) was a pursuit to produce more predictable electrical responses, encapsulate components into protective casings, and extend lifespan. Here, we delineated the growth of *P. polycephalum* memristors and created a microenvironment where environmental variations can be better controlled. Results of our receptacle's testing have demonstrated that our design has significantly decreased growth time, increased lifespan, and standardised component responses.

Due to our progress on standardising the components, we are now able to turn our attention to studying the biological function responsible for the organism's memristive abilities. An exciting prospect of using biological components is that they display complexities that might be harnessed to augment their usage. We have been conducting experiments to investigate the hypothesis discussed in Section 8.2, where we expressed our belief that voltage-gated ion channels play a role in memristance. These experiments have involved altering extracellular ion concentrations and observing the subsequent effects on the organism's I-V profile. Our preliminary experiments have shown that the resistance switch becomes exaggerated with increased external calcium (CaCl_2) concentrations (Figure 8.21). We are also in the midst of investigating the effects of other stimuli on the cell's conductance; for example, temperature, pH, light and pressure. If we can gain an understanding of the memristive mechanism, we may be able to establish parameters for controlling its memristance. It is plausible to envisage a system that would produce different sounding responses by changing the hysteresis of its memristors.

Our research is committed to taking *P. polycephalum*-based memristor technology out of the laboratory and into the real-world. As UC for CM is very much in its infancy, we are yet to fully understand how these new types of technologies may benefit music.

8.5 Questions

1. Are we likely to progress past today's conventional computing paradigms that are derived from the Turing Machine and von Neumann architecture?

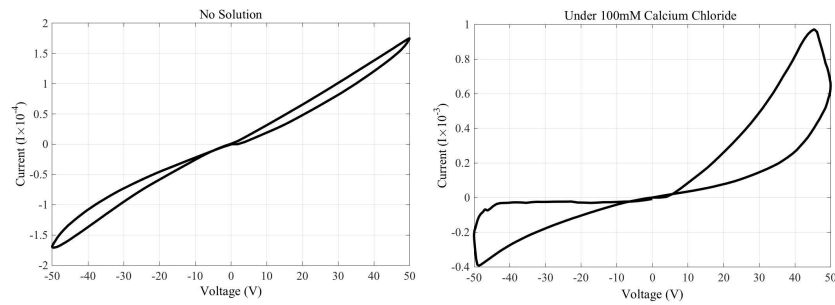


Fig. 8.21: A comparison of two I-V profiles recorded on *P. polycephalum* memristors. The graph on the left was measured on a memristor under normal testing conditions. The graph on the right was measured on a memristor that had been treated with 100mM of CaCl_2 .

2. What might be the benefits of integrating biological systems into our technology?
3. Is it important for computers to be universal? (e.g. one model fits all problems)
4. How could technology put forward by the field of Unconventional Computation impact the music industry?
5. What form might future computing devices take?
6. How might the memristor change the way our computers function?
7. How could progress in Unconventional Computing be made more visible to creative practitioners?
8. Can Unconventional Computing benefit from Computer Music research?
9. What challenges might a musician face when deploying Unconventional Computing systems in music?
10. Can musical research with *Physarum polycephalum* help disseminate the potential of biological computer for music?

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